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Unterhaching geothermal well doublet: structural and hydrodynamic reservoir characteristic; Bavaria (Germany)

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ABSTRACT

At Unterhaching, two wells – Gt Uha1a for production, Gt Uha2 for injection – were drilled and tested for the cogeneration of electricity and heat. Very high productivities of both could be determined. These good inflows are attributed to the influence of fault systems. In particular, the well Gt Uha2 was drilled through a fault with a vertical throw of 238 m. At the top of the aquifer, the temperature of the produced water was 123 °C (Gt Uha1a) or approx. 134 °C (Gt Uha 2). The high temperatures in the Gt Uha2 well are ascribed to waters circulating in a deep-reaching fault system. Inflows within the Malm come exclusively from the Upper Malm (Malm Zeta).

1. INTRODUCTION

A geothermal cogeneration plant will be constructed at Unterhaching which is a community located on the southern outskirts of Munich / Bavaria (Germany). It shall supply heat to a part of the community. Surplus heat arising especially in the summer shall be used for electricity generation.

The future cogeneration plant is based on a well doublet consisting of the production well Gt Unterhaching 1a (Gt Uha1a) and the injection well Gt Unterhaching 2 (Gt Uha2) drilled from 2004 – 2007. In this paper, the relevant geological, drilling-engineering and hydraulic test data are given and discussed, highlighting the particularities of the geothermal Malm aquifer south of Munich. For the Unterhaching project, the Malm was to be developed at a total vertical depth (TVD) of 3,000 – 3,350 m.

1.1 Regional Geology of the Molasse Basin

The Molasse Basin is situated in S Germany and limited by the Northern Calcic Alps or the folded molasse in the south, the Franconian Alb and the Svabian Alb in the north, the Bavarian Forest / Bohemian Massif in the East and the Swiss or French Folded Jura in the West. The basin is approximately 700 km long (WSW-ENE) and approx. 250 km wide (NNW-SSE). The main part of the Molasse Basin is situated on German territory extending to Austria, Switzerland and France. The Molasse Basin contains Oligocene and younger sediments being up to 5000 m thick at the edge of the Alps.

300 million years ago, during the Permian, the present Alpine piedmont consisted mainly of granites and gneisses (Lemcke 1988). In the course of another several million years, this base rock was covered by Mesozoic and younger sediments from west to east. First clastic sediments deposited during the Rotliegend and the Buntsandstein stages in the west of the Molasse Basin. Subsequently, the Muschelkalk sea transgreded from the north, extending the sediment cover towards the east. This tendency continued also during the Keuper and the Lower and Middle Jurassic, reaching approximately the present site of Munich. During the Malm, the sea had its largest extension (total flooding of the present Molasse Basin territory) reaching the Bohemian Massif and flooding it partially. In the south, the sea was rather deep, with the other parts being relatively shallow. The palaeo-landscape was characterised by coral and sponge reefs with lagoons in between. At that time, the Munich area was marked by distinct reefs.

Subsequently, the sea vanished almost completely from the present area of the Molasse Basin. During the Cretaceous, the sea advanced again from the south, being limited, however, to the present territory of East Bavaria (largely around the present area of Munich). At the end of the Cretaceous and with the beginning of Tertiary sedimentation, the territory of the present Aline piedmont turned into a foredeep of the Alpidic Orogene and the formation of the Molasse Basin began (Lemcke 1988).

The Tertiary Molasse Basin itself has to be considered as an orogenic foreland basin of the Alps. Such basins were connected all over again with the Thetys. These effects are reflected in the sediments of the Upper and Lower Marine Molasse. When the marine influence was small, predominantly sediments of the Upper and Lower Fresh-water Molasse deposited. Mainly carbonates, marl and limy fine sandstones accumulated.

1.2 Molasse Basin - the Malm

During the Malm, totally different habitats existed on the territory of the present Molasse Basin which is reflected by the different formation of the Malm rocks.

Developing from the south, alpine (helvetic) facies reached far into the present territory of the Alps interlocking with the Teutonic (Svabian) facies.

The Helvetic facies which sedimented in the deep sea is characterised by bituminous Quinten lime. These platy and thickly bedded limes mark the clay marl and hornstone strata. Such formations advanced far into the east in the Malm Alpha (deepest part) drawing back again in western direction by the Malm Zeta (target section).

There exist a SSE-NNW striking epeirocracy of the base rock in the Landshut-Kehlheim region which formed an island in the Malm sea. Barrier and fringing coral and sponge reefs formed around this island, too. More reef systems formed on the present territory of Munich.

Lagoons were situated in between these reef systems where sandy carbonate muds accumulated. These lagoons are characterised by fine interbeddings of marl and carbonate rocks.

The karstification of the Malm carbonates is the reason for the predominantly good hydraulic properties of this most important geothermal aquifer in S Germany. Mainly, the karstification is restricted to sections with large fault systems and the carbonates of the reef facies showing already good conditions for the flowing meteoric waters. Moreover, sections with large fault systems for the transport of huge water quantities are known. The dumping of the South German Major Block is understood to be the cause of this karstification. The rocks were shifted underneath the Alps in the south and in the northern part of the Block either to the surface or very close to the surface allowing for penetration and drainage of water. The northern sections of the Malm in the Molasse Basin are karstified more as they were exposed longer to the surface. In the Svabian and the Franconian Alb, the Malm carbonates form rocks. Karstification can be observed here at numerous places.

Generally, karstification decreases from N towards S, so that predominantly fault zones act as flow paths in the south. But only in the south, the Malm reaches > 3 km and, thus, temperatures > 110 °C allowing for geothermal electricity generation. Due to the only insignificant karstification of the lime rocks in the south, faults have to be connected in order to achieve high productivities of the wells. Partly, the rocks are broken up heavily within these fault sections showing, in addition, several accompanying faults.

1.3 Geological and Tectonical Conditions

The Malm with its total thickness of approx. 600 m is deposited in the area S of Munich at a depth ranging from 2,500 – 4,000 m. Only the Upper Malm (Zeta) is to be considered as suitable here being 350 to 400 m thick.

The area S of Munich is characterised by a series of NE-SW striking antithetic faults. Unger (2005) postulates a NNW to NW striking lateral fault with one of the parallel associated faults being proven in the Gt Uha 1 well by means of VSP measurements (cf. Thomas 2007, Thomas & Schulz 2007). The well Gt Uha 1 was drilled directionally into this NNW to NW striking fault. Probably, it reached the loosening zone near this fault. Thus, a hydraulic communication of the well with the fault or the fault system is possible.

The Uha Gt2 well was directed into an NE-SW antithetic fault system (Unger 2005, 1999, Bayrischer Geothermieatlas 2004) characterised by totally very high levels of filling reaching up to approx. 240 m (Fig. 1) with the upper block being located in the NW and the lower block in the SE. In the Molasse Basin, the fault systems are connected with each other so that a communication of the wells is guaranteed.

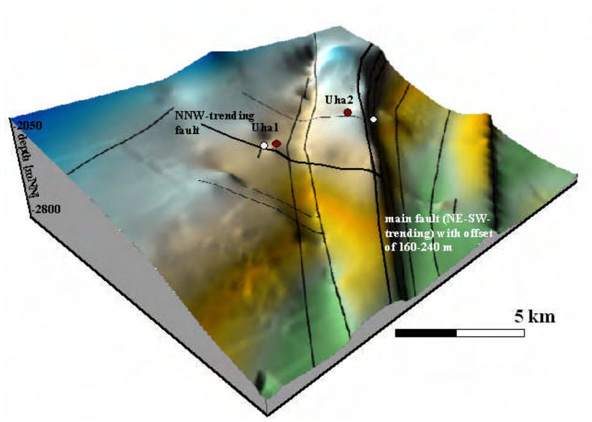

Figure 1: Schematic figure of the top of the Malm in the Unterhaching area with main structures acc. to maps and data by Unger (1995, 2005), Bayerischer Geothermieatlas (2004), Thomas (2007) as well as data obtained from Unterhaching wells. Red spots – surface locations of the wells, white spots – final locations of the wells

2. HISTORY AND GEOLOGY OF UNTERHACHING WELLS UHA GT 1, GT1A, GT2

2.1 History

The well Gt Uha1 was drilled from 25.1.2004-19.09.2004 down to a depth of 3,446.0 mMD (3,350 mTVD). Starting at 2,858 mMD, the final branch was drilled (Gt Uha 1a) down to the above final depth. Having reached the Malm, little mud losses occurred only. Acidification was done in the well (7.5 % hydrochloric acid) producing a pressure build-up of 16.4 bar which dropped to 0 suddenly. Obviously, this acidification resulted in the connection of the well to the reservoir and / or developed a fault zone. Actually, the Gt Uha 1a well is planned to be the production well.

The well Gt Uha2 was drilled from 22.06.2006 to 12.11.2006 down to 3,595,0 mMD (3,331.4 mTVD). Since the hydraulic parameters required for the project could not be achieved after the first hydraulic tests, it was decided to deepen the well. So, it became clear after the analysis of the mud samples and evaluation of the well-log that after a depth of 3,540 mMD (fault zone), again the top Malm was drilled through. Thus, the well past at first the Upper Malm reaching then the fault in the trench block where the Upper Malm was drilled through again. Along with the antithetic fault, associated faults could be assumed in the south. On 12.01.2007, the final depth of 3,863.7 mMD (3,590 mTVD) was reached. Mud losses occurred after 3,390 mMD and increased after 3,450 mMD. The well was deepened (due to technical reasons) with total mud loss. Moreover, acid stimulations were done. the deepening of the well. Thanks to the acidifications prior to the deepening of the wells, the biggest inflow section in this zone could be connected at 3,340 mMD. The Gt Uha2 well is designed for injection.

2.2 Technical Well Parameters

The wells were completed according to the parameters given in Table 1. The reservoir section of the Gt Uha1a well was secured by means of a slotted liner, whereas the Gt Uha2 well represents the open-hole variant by now.

Table 1: Casing of the Gt Uha1a, Gt Uha 2 wells

	Gt Uha1a		Gt Uha2	
	depth [mMD]	dia-meter	depth [mMD]	dia-meter
conductor pipe	0 - 34	28“	0 - 35	22“
anchor pipe	34 - 799	18 $^5/_8$“	35 - 750	16“
intermediate casing	- 816	16”	654 - 1842	13 $^3/_8$“
intermediate casing	-1935	13 $^3/_8$“	1748 - 3169	10 ¾“
intermediate casing	1829 - 3012	9 $^5/_8$“	2675 - 3075	8 $^5/_8$“
open hole, slotted liner	3000-3446	7 “	3169 - 3864	9 $^5/_8$“

The Gt Uha1a well was deviated after 2858 mMD towards 315 ° with an inclination of approx. 33 °. The final depth achieved was 3446.0 mMD or 3350 mTVD.

The Gt Uha2 well was deviated after 1848 mMD towards 154 ° with an inclination of approx. 25 – 40°. the final depth achieved was 3863.7 mMD or 3590 mTVD.

2.3 Stratigraphy and Lithology

Stratigraphy and lithology of the Unterhaching wells are presented in Table 1. The Malm as the target horizon is reached at a depth of approx. 3,000 m TVD.

Table 2: Brief well-log of the Gt Uha1a, Uha2 wells; f.d. – final depth, TVD – total vertical depth, m b.s. – meter below sea level

Stratigraphy	Uha 1a m b.s. TVD	Uha 2 m b.s. TVD	Lithology
Quarternary	-28	-20	gravel, sand
Miocene	-1690	-1685	sand, marl, schluff, limy
Oligocene	-2845	-2785	clay marl, lime marl, claystone
Eocene	-2910	-2875	Limestone, lime marl, sandstone
Upper Cretaceous	-2930	-2905	lime marl
Lower Cretaceous	-3002	-2977	Limestone, lime marl, claymarl, sandstone, breccia, limestone
Jurassic (Malm)	-3350 (f.d.)	-3590 (f.d.)	limestone, dolomite

In the well Gt Uha2, there could be identified two strong fault systems in the Malm carbonates, the first one at 3115 mTVD, and the second one at 3294 mTVD. The second fault is characterised by a fault throw of 238 m (following gamma-log interpretation), with the horst (upper) fault block in the north and the trench (lower) fault block in the south. The faults are interpreted as intrajurassic faults, therefore the Upper Malm and the Cretaceous on the trench block must be a little thicker.

2.4 Malm in the Wells

In both wells, the Upper Malm (Malm Zenta) is developed, respectively – in addition, the stratigraphic sequence up to Malm Gamma in the Gt Uha1 well.

Lithologically, the Malm Zeta has a very differentiated structure. Mainly, however, it consists of massive limestones. In the upper third of both wells, a 30 – 40 m thick dolomite or dolomitic limestone layer is located which can apparently be identified by a positive anomaly according to the temperature-log. Basically, the Malm Zeta limestone has to be described as cryptocrystalline, porous, white limestone. In the deep part of the Gt Uha2 well, this limestone is transformed into a beige coarse-crystalline limestone in the near-fault zone. Obviously, these are De-dolomites, i.e., originally diagenetically dolomitised rocks re-transformed subsequently into limestones.

The Malm Gamma in the Gt Uha1a well which can be identified by its increased activities in the gamma-log is proven by a layered structure and the occurrence of pyrite and clayey marlstone.

Investigations into the lithology and facies of the Malm in both wells are going on within the framework of a research project. Results have not been presented by now.

2.5 Temperatures in the well Gt Uha 1a, Gt Uha2

For the planned geothermal use, in particular, those temperatures are important which were measured in the reservoir section during the tests, as these allow for conclusions regarding the later efficient temperature. So, a maximum temperature of 123 °C of the produced fluid could be determined during the test in the Gt Uha1a well. In the Gt Uha2 well, even 133.7 °C were measured (measuring probe at approx. 2,952-2,258 mTVD, respectively). It has to be mentioned that only 129.0 °C were measured during the tests before this well was deepened.

The temperature at the top of the Malm could be determined based on different temperature-logs and measurements of the temperature behaviour. 121.7 °C were measured at a depth of 3002.4 mTVD of the top Malm in the Gt Uha1 well (GGA institute, 19.10.2006) , and 124.5 °C at 2,977 mTVD (GGA institute, 21.3.2007) in the well.

The clearly higher production temperatures in the Gt Uha2 well are assumed to be due to the fact that, on the one hand, deeper fault zones in the Malm were connected here, and on the other hand, deep water circulation in the fault zone provided for partial balancing of the temperature.

3. HYDROGEOLOGY

For the reconstruction of the hydrogeological conditions in the area under investigation and in order to prove the productivity / injectivity of the drilled wells, production tests were carried out in both wells. During the production tests in the Gt Uha2 well, the pressure was measured in the Gt Uha1a well to show whether the drawdown funnel could reach during the tests in well Gt Uha2 the Gt Uha1 well which is located approx. 3 km away.

At present, a circulation test is going on. For that, the fluid is produced from the Gt Uha1a well and fed into the Gt Uha2 well via a pipe system. The pressure heads are measured in both wells. This test is accompanied by a comprehensive investigation and analysis programme.

In the following, the results of the production tests in the wells are presented and assessed.

3.1 Hydraulic Tests in Uha Gt1a

The test interval of the well ranged from 3,012.0 to 3,446.0 mMD. Here, the Malm was developed and protected by a slotted liner.

Air lift tests were done. At a depth of 2,958 mMD, the p/T tool was installed for online pressure and temperature recording. The performance test lasted 114 hours, with Malm water being produced at flowrates of 50 – 67 L/s (stage test) in the first 50 hours, followed by the measurement of the pressure build-up over a period of 64 hours. The static pressure of the Malm aquifer could be determined to be 267.4 bar (2,958.93 mTVD). As a consequence of the tests, the pressure dropped by 7.7 – 11.8 bar, Based on the test data, transmissivities ranging from 2.8 – 4.0 * 10^{-4} m^2/s could be identified. The well shows a strongly negative skin factor of –5.4 - -6.0 indicating that the well is excellently connected to the reservoir. The ongoing circulation test shall show whether these transmissivities are sustainable or not.

3.2 Hydraulic Tests in Uha Gt2

Having achieved the initially planned target depth of 3,595 mMD, 3 performance tests and 1 injection test were carried out with the performance test 3 (LT 3) being representative in the sense of the test data and which is referred to in the following. Here, the test interval was 3,169.5 – 3,595 mMD.

During the LT 3, water was produced over a period of 60 hours, i.e., for 24 hours at a flowrate of approx. 30 L/s, and then at a flowrate of approx. 40 L/s over a period of 36 hours with the rates getting relatively stable gradually. After that, the pressure build-up was measured (p/T tool at 2,952 mTVD) over a period of 75 hours. The evaluation of the Horner plot and other pressure values resulted in a static pressure of 267.7 bar. The depression at the end of the tests is amounted 24.8 bar. Thus, low productivities could be determined for the LT 3 according to the respective flow pressure. With these values, the objective of the well (150 L/s) could not be achieved. For this reason, the well was drilled deeper and tested again.

Having drilled the well deeper down to 3863.7 mMD, another performance test was carried out (LT4, Fig. 2). Here, the test interval ranged from 3,169.5 – 3,863.5 mMD. After initial high flowrates, a flowrate of approx. 80 L/s appeared after 24 hours which still dropped slightly. As the pressures dropped as well, special demands were made on the evaluation of this test. A second rate could be considered to be almost stable at approx. 55 L/s. During this test which lasted totally 110 hours producing 13,806 m³ of water, high productivities could be determined. The depression at the end of the tests is amounted 4.2 bar. However, the conditions were not stationary yet. Comparing the tests in both wells, it becomes obvious that the productivity in the vicinity of the Gt Uha2 well is approx. twice as high as that in the vicinity of the Gt Uha2 well. The transmissivity was determined to be 4.6 – 7 * 10^{-4} m^2/s. The negative skin factor of 4.1 shows the good connection of the well to the reservoir.

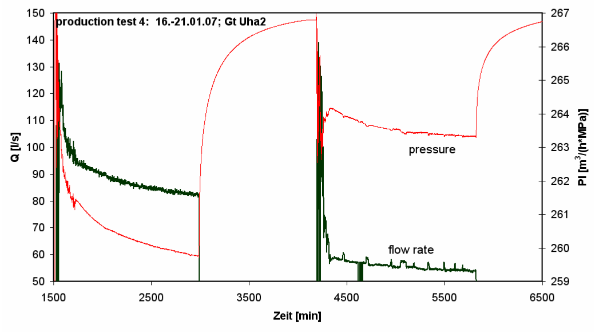

Figure 2: Performance test 4 of the well Gt Uha2, pressure behaviour (red) and production flowrate behaviour (dark green) during the test

3.3 Testing of the Reservoir Between the Uha Gt1 and Gt2 wells

During the test work in the Gt Uha2 well, a consistency gauge was installed in the Gt Uha1a well at a depth of 300 m. With a approx. 24 h delay after the beginning of the test, one pressure signal (as a reaction to the tests in Gt Uha2), respectively, could be observed in the Gt Uha1a well and correlated without any doubt. The maximum pressure drop was 1.2 bar. Through adaptation of the measured pressure curve, transmissivities of 10 – 11 * 10^{-4} m^2/s could be determined. These are effective mean transmissivities characterising the reservoir in between the two well, thus being bigger on an average than that in the vicinity of the individual wells themselves.

3.4 Inflow Sections

For identification of the inflow sections and aquifer thickness, the temperature behaviour was measured in both wells after cold water injection, respectively. In addition, the flow was measured in the well Gt Uha1a.

According to the flow-log, waters flow in within a range of depth of 3,100 – 3,341 mMD (vertical thickness approx. 202 m) in the well Gt Uha1a with 3 sections showing major inflows. Withing a range of depth of 3,100 – 3,155 mMD, 27 % of the overall inflow comes from a limestone with a saccharoidal matrix. Underneath that, a 9 m thick reef-detrital limestone is developed delivering 15 % of the overall inflow. The deepest inflow horizon is formed by a layer of 18 m thickness consisting of dolomitic, slightly cavernous limestones which deliver 27 % of the overall inflow (Figure 3). It is assumed that the inflow sections of the well were fractured by the nearby fault zone which led to the good hydraulic characteristics of the aquifer at the site of the well. The inflows end up approx. 50 m above the Malm Gamma. Moreover, it has to be mentioned that the inflows decrease strongly above the dolomites at 3,164 mMD. The temperature-log shows a significant deflection here (Figure 3). In addition, the temperature-log indicates groundwater circulation in the Purbeck section (2972 - 3002 mTVD), as a weakly negative temperature gradient exists here.

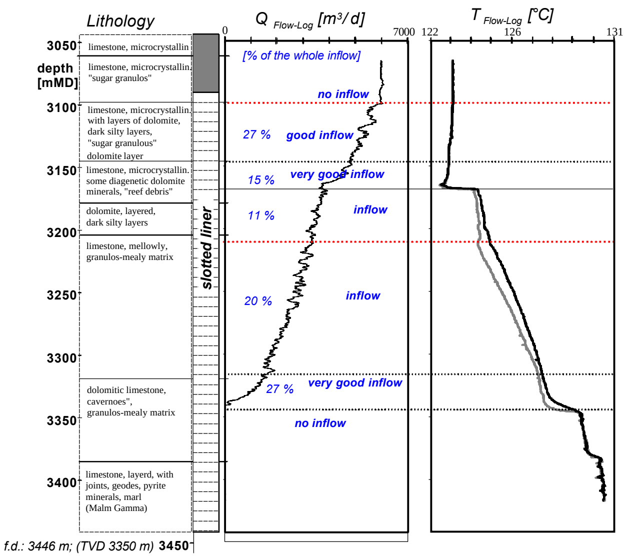

Figure 3: Inflows in the Gt Uha1a well acc. to flowmeter-log and temperature-log

In the Gt Uha2 well, only the temperature log can be applied for identification of the inflow sections. Prior to logging, cold water was injected in the well. However, logging was done in the top inflow section at a depth of approx. 3,340 mMD.

While drilling, the first mud losses occurred at 3,480 mMD. More signs of inflow sections are given by the results of the performance tests before and after the deepening of the well. The well productivity increased very much after that deepening. It results therefrom that approx. ¾ of the inflows come from the section between 3,595 and 3,700 mMD. The overall inflow interval can be ascribed to the section ranging from 3,330 – 3,700 mMD (cf. Figure 4) corresponding to a vertical thickness of approx. 335 m. The reason of this large thickness is the fact that the well coming from the horst fault block passed a main fault at 3,540 mMD, developing the Malm again in the trench fault block. The inflows end up at 3,700 mMD – which – according to the geological data - should happen approx. 50 m above the Malm Gamma which, however, was not developed by the well. A part of the main inflows come from the fault at 3,340 mMD, the major part, however is delivered from a section after the main fault, i.e., below 3,540 mMD. Obviously, this zone reaching from the fault to the trench fault block is strongly fractured. This section which is tied to the fault delivers the main inflow. The matrix of the Malm supplies minor inflows across the entire section, as already stated for the Gt Uha1a well.

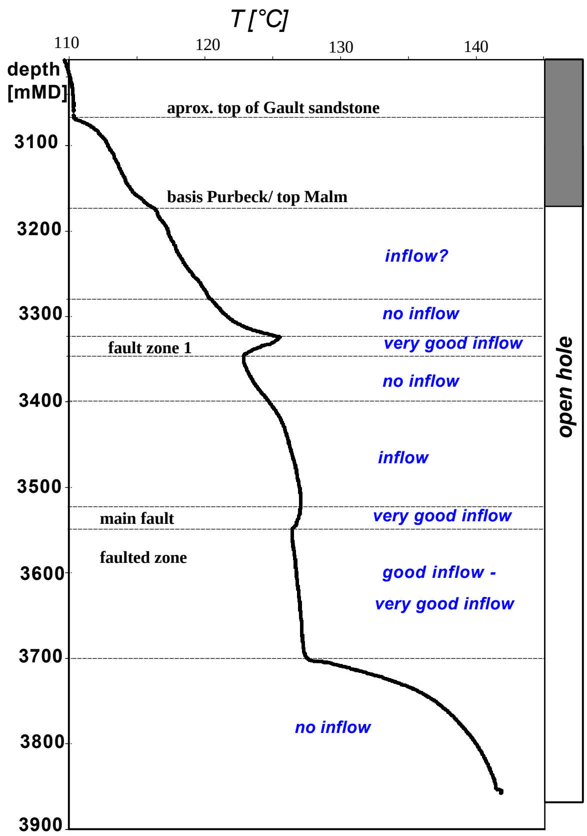

Figure 4: Inflows in the Gt Uha 2 well acc. to temperature-log (GGA institute, 21.3.2007), temperature-log was measured after a cold water injection;

3.5 Fluid and Gas Composition

Deep samples were taken from the Unterhaching wells after the productions tests: 1 sample from the Gt Uha1a well at a depth of 3,000 mMD and 1 sample from the Gt Uha2 well at a depth of 3,200 mMD. Water of both wells contain salinities of 600 mg/l to 1000 mg/l. The main component is hydrogen carbonate with values about 300 – 400 mg/l. The pH was measured to be 8.8 during the hydraulic test. This value is typical for Malm waters in the Molasse Basin. Also the H_2S values are relatively low for Malm waters with the maximum value being measured to be 2 mg/L. The gaseous phases are well analysed for Gt Uha1. While the gas content in both wells was measured to be 30 – 50 Nml /L, exact analyses are available only for Gt Uha1a at present. Here, the main phase is formed by CH_4 with approx. 60 %, followed by N_2 with approx. 30 %. Isotopic data of both wells vary from -10,1 – -11.8 ‰ for ^{18}O, as well as –67.7 - -87 ‰ for deuterium.

Generally, the water analyses show typical signatures of Malm water, with small variations resulting from former activities in both wells.

4. CONCLUSION

The wells Gt Uha1a and Gt Uha2 developed the Malm at a depth of approx. 3,000-3,600 mTVD.

Only the Upper Malm (Malm Zeta) serves as aquifer which is approx. 350 m thick. It consists of cryptocrystalline, white, finely porous limestones.

In hydraulic tests, transmissivities ranging from approx. 2.8 – 11.1 * 10^{-4} m^2/s could be determined. According to the results of further investigations, the reservoir in between the two wells are characterised by high effective mean transmissivities exceeding those of the near-well area. These good hydraulic properties are attributed to the positioning of the wells in the area of fault zones. In particular, the NW-SW master zone appears to be responsible for high fluid inflows. Due to the high fault throw of 238 m, obviously a series of associated and auxiliary faults was generated strongly loosening the rocks in this section. E.g., similar conditions exist in the Thermal Riem 2 well (Wenderoth et al. 2005) reaching the Marktschwaben fault throw.

The inflows in both wells occur via a thickness of totally 200 – 300 m. However, the main inflows are restricted to a few sections, respectively.

The temperatures in both wells amount to 121.7 °C and 124 °C, thus being higher than they could be assumed to be based on the available regional data (Geothermal Map of Bavaria). The high fluid temperature of approx. 134 °C measured during the tests in the Gt Uha2 well are ascribed to fluid circulation in a deep-reaching fault system.

The fluid chemism indicates a typical Malm water composition characterised by salinities < 1g/L and containing mainly hydrogen carbonate. An important fluid phase is H_2S.

Acknowledgements

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